The Fundamentals and Status of Nuclear Power

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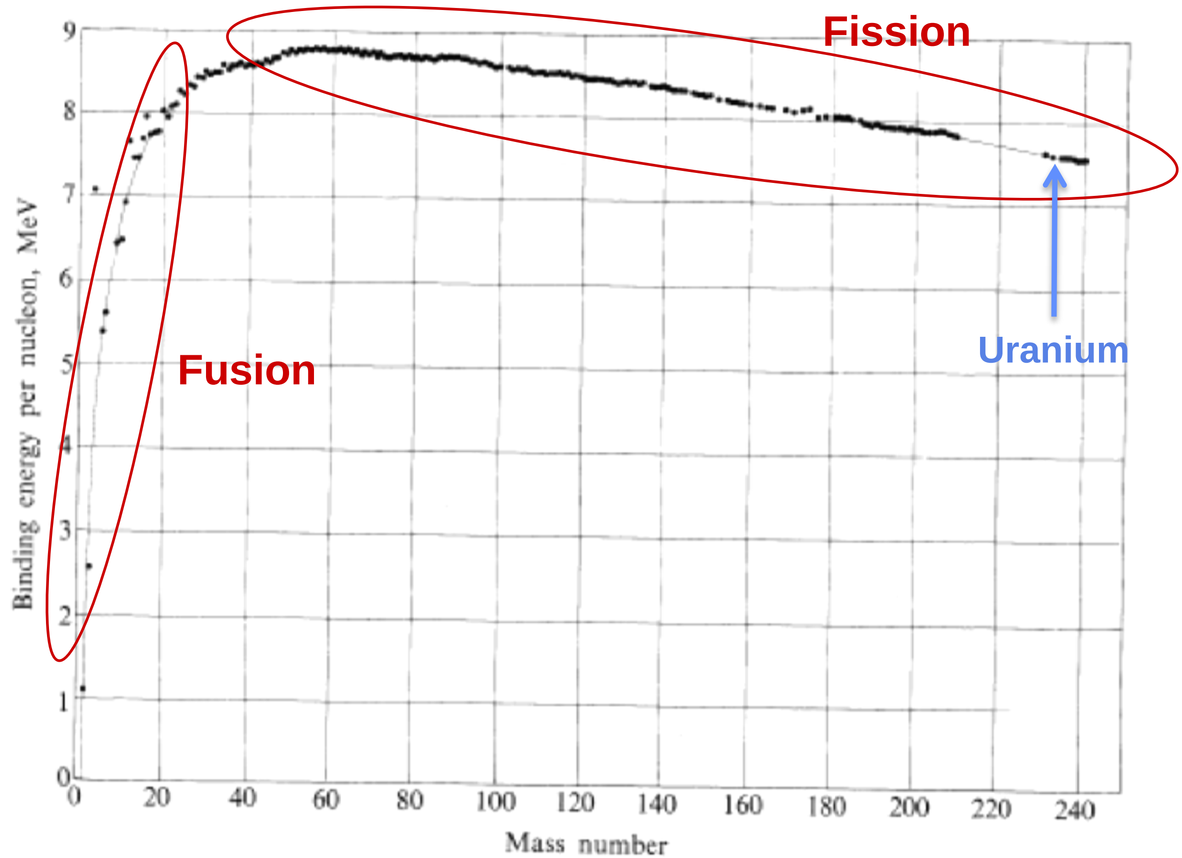
Amherst, MA

Binding Energy of the Atom

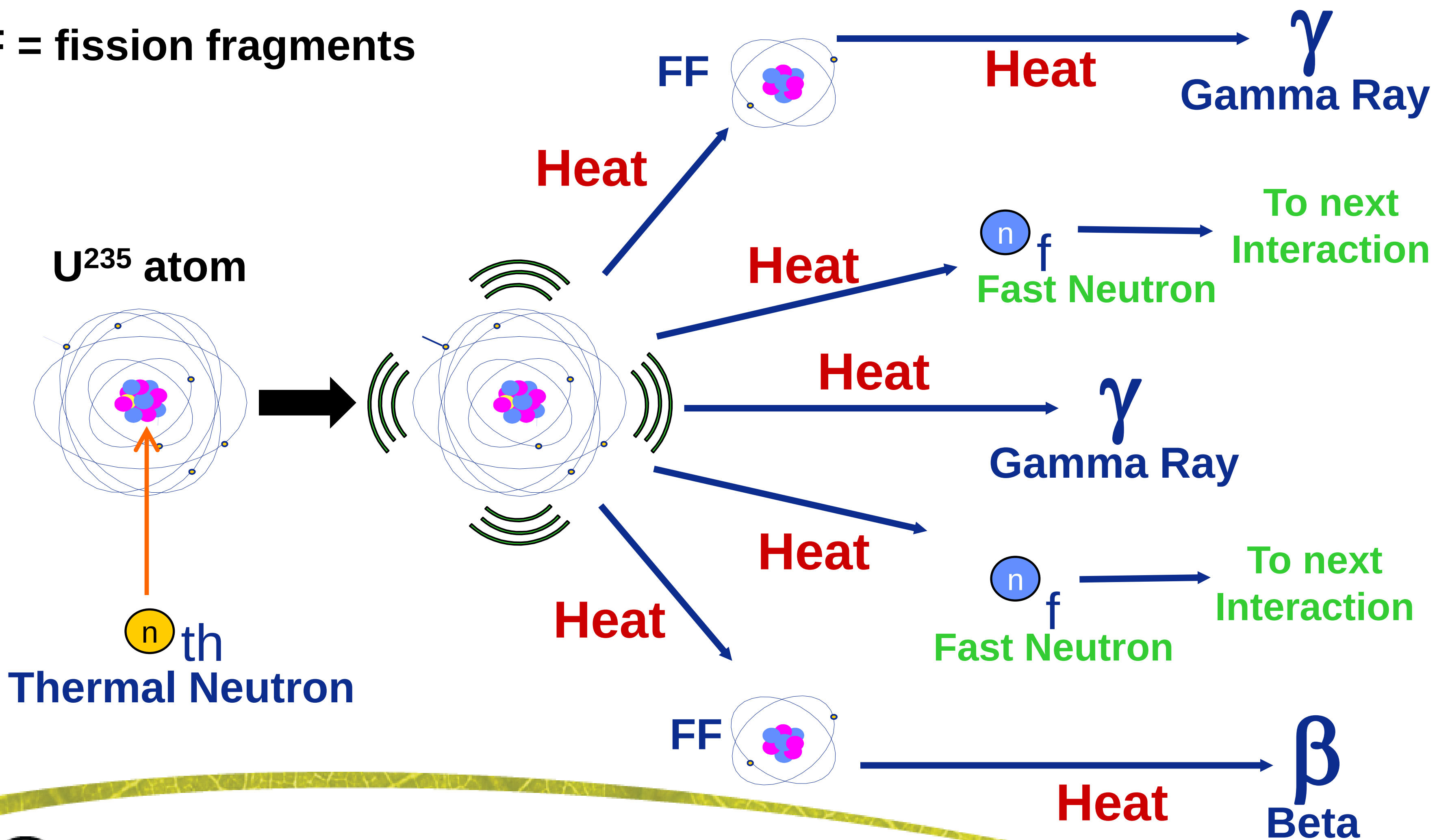
Energy with which the nucleus is held together



When an Atom is split, the mass of all particles is slightly less than originally – the missing mass is converted to energy ($E = mc^2$)

Energy Releases from U^{235} Fission

FF = fission fragments

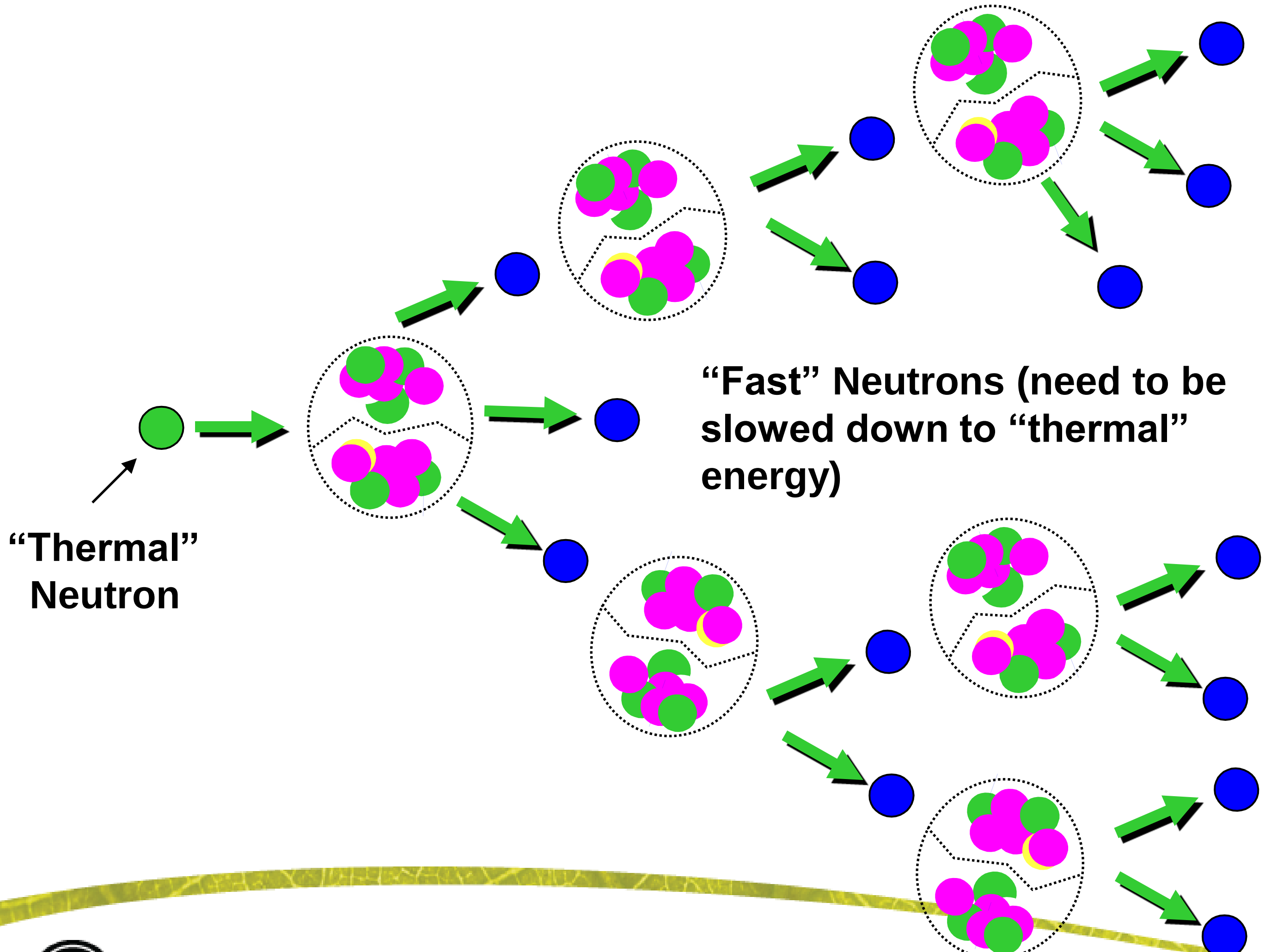


Typical Energy From U^{235} Fission

Form of Energy Released	Amount of Energy Released (MeV)
Kinetic energy of two fission fragments*	168
Immediate gamma rays	7
Delayed gamma rays	3-12
Fission neutrons (typical)	5
Energy of decay products of fission fragments	
Gamma rays	7
Beta particles	8
Neutrons	12
Average total energy released	~215 MeV

* Can be two or more fission fragments

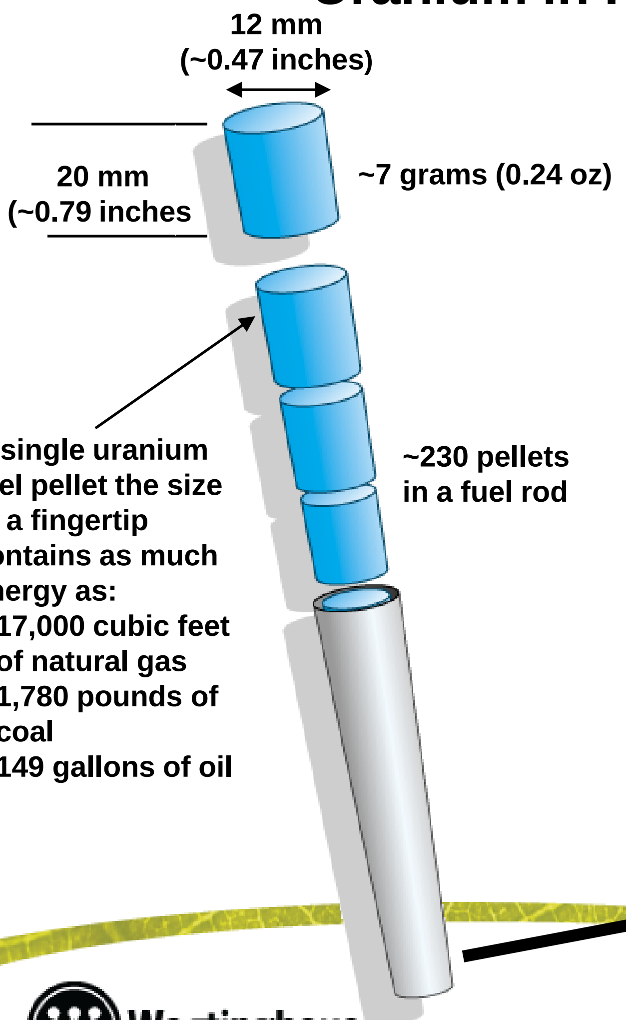
Splitting the Atom



On average, the fission of U^{235} produces 2 or 3 neutrons. ***If at least one neutron from each fission event collides with another U^{235} nucleus and causes fission, then a nuclear chain reaction is sustained*****.**

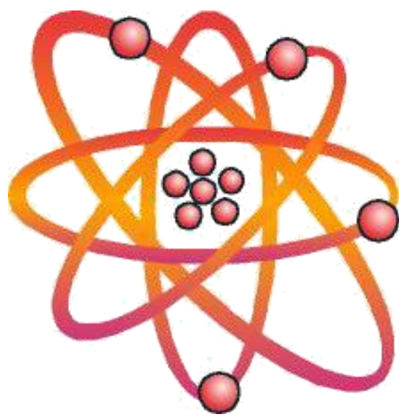
Nuclear Fuel

Uranium in Fuel Pellets enriched to ~4.0% U^{235}

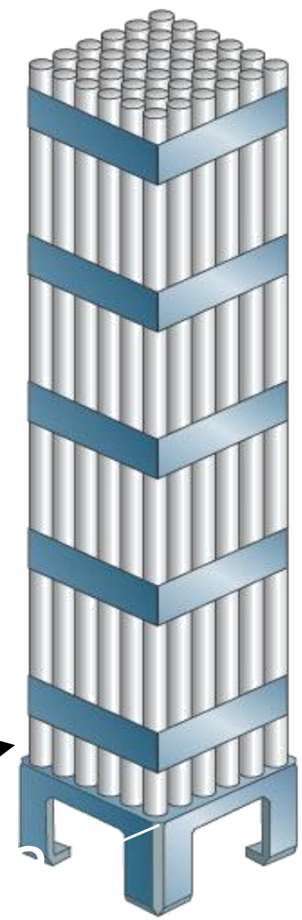


A single uranium fuel pellet the size of a fingertip contains as much energy as:

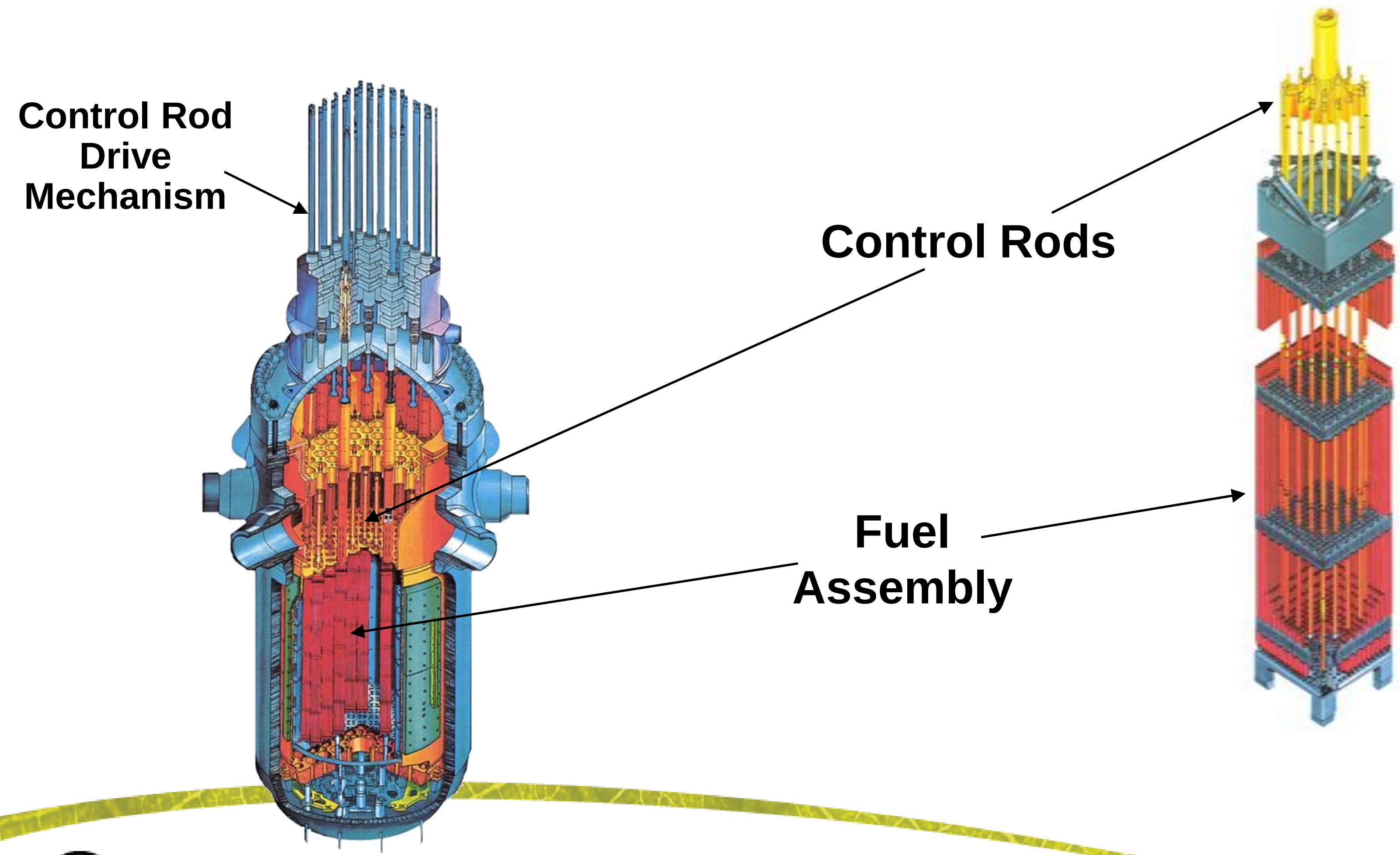
- 17,000 cubic feet of natural gas
- 1,780 pounds of coal
- 149 gallons of oil



$^{235}U_{92}$

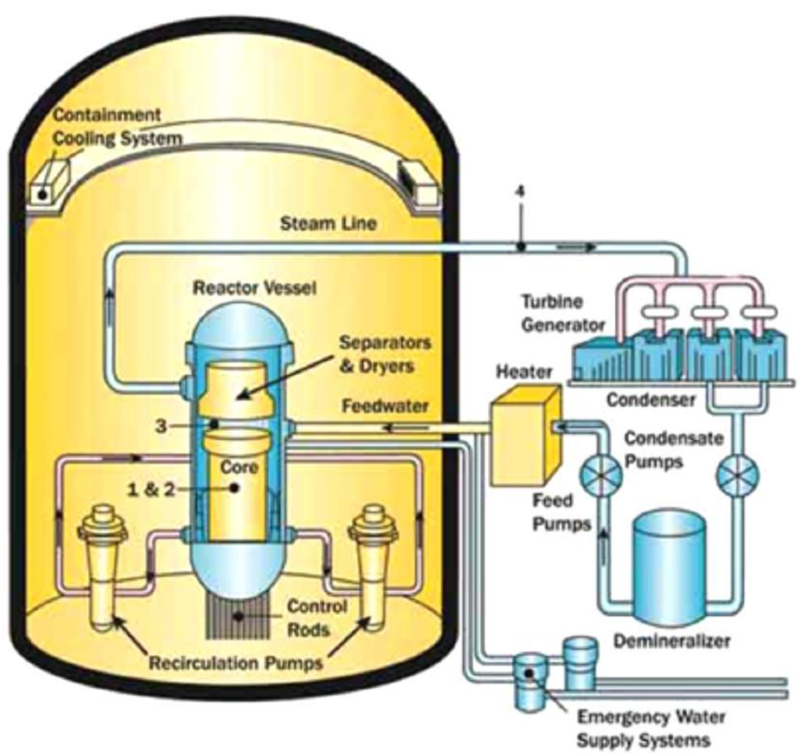


Nuclear Reactor
Reactor Core and Control Rods

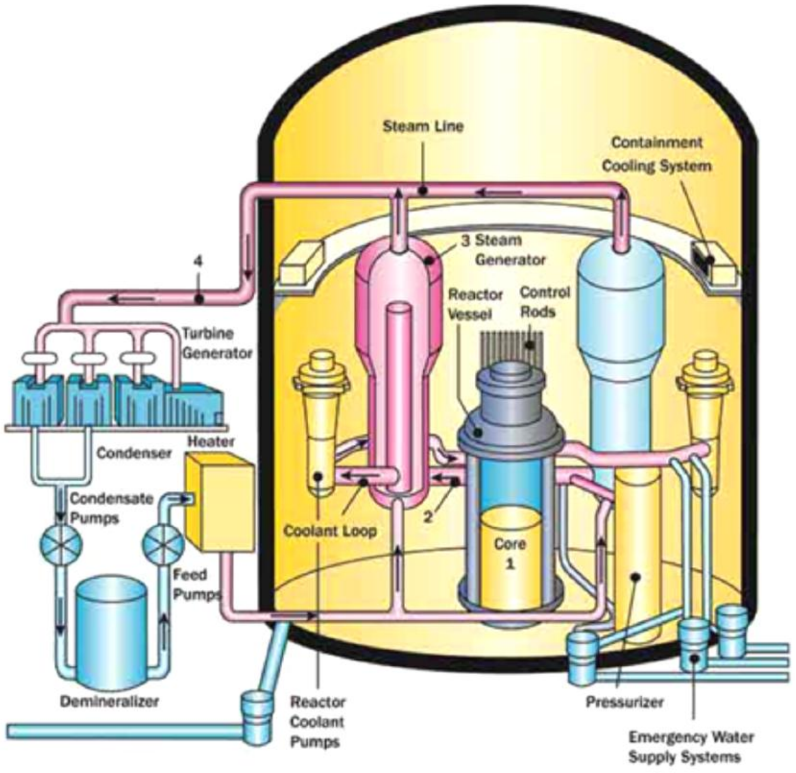


Most Common Types of Reactors Operating Today

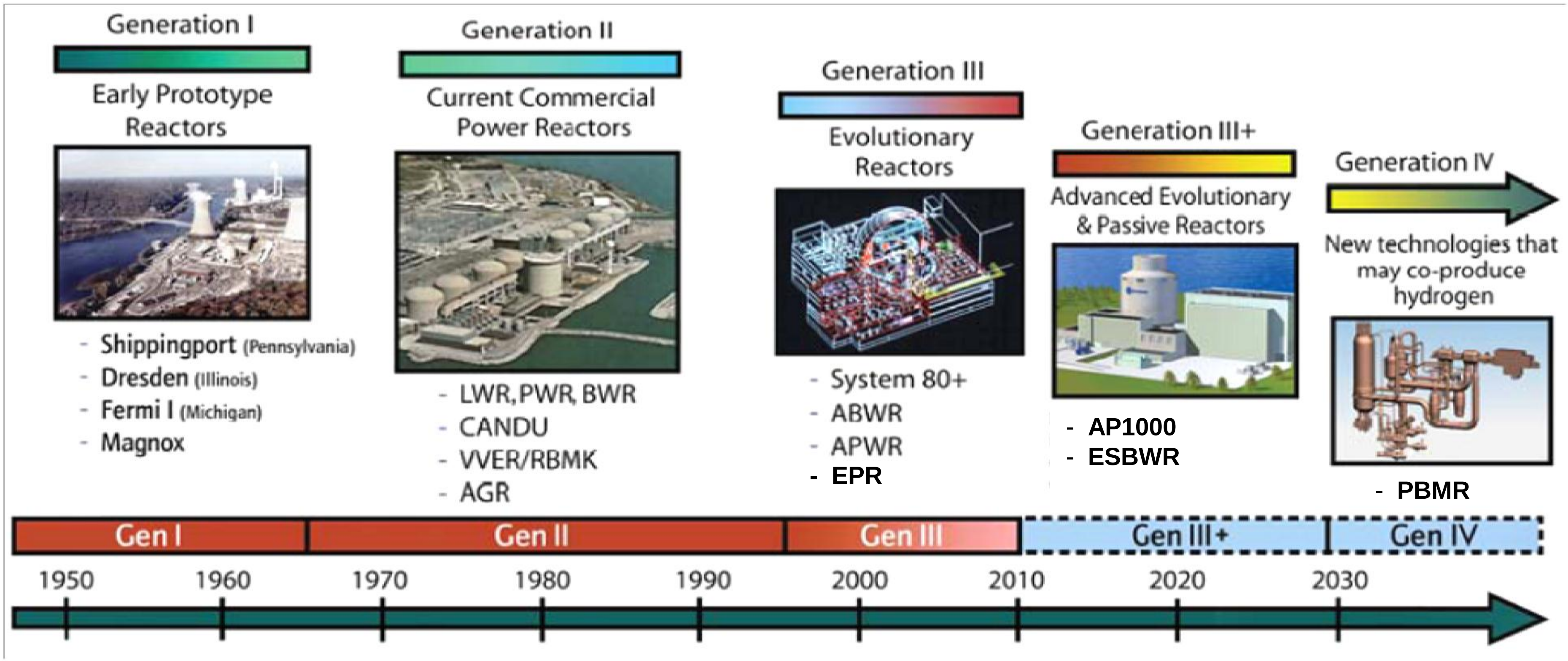
Boiling Water Reactor (BWR)



Pressurized Water Reactor (PWR)

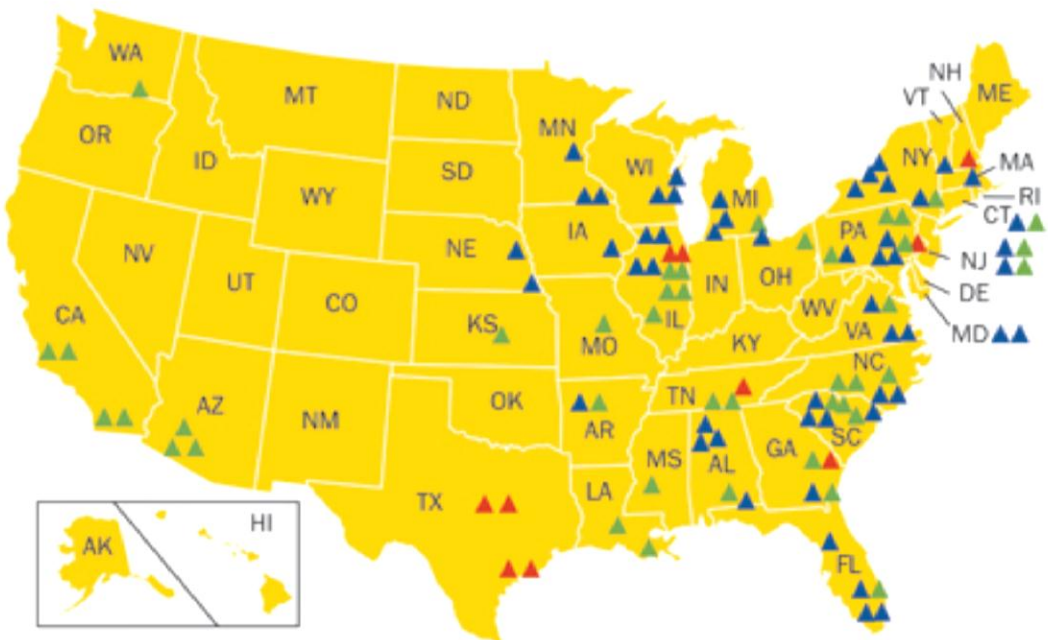


Evolution of Nuclear Power
(from 1950s to 2030)



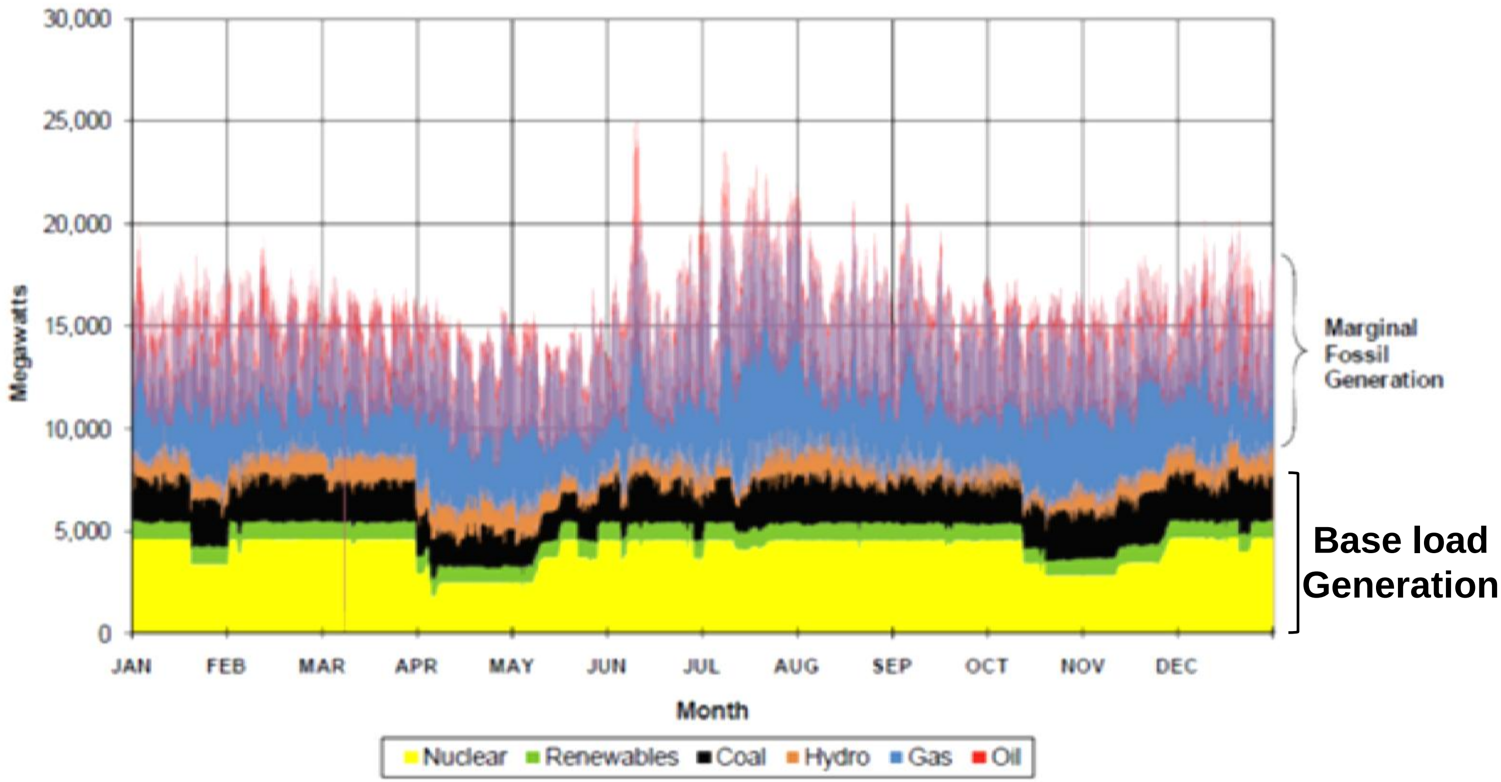
U.S. Power Reactors in Operation
(104 mostly in Eastern States)

U.S. Commercial Nuclear Power Reactors—Years of Operation



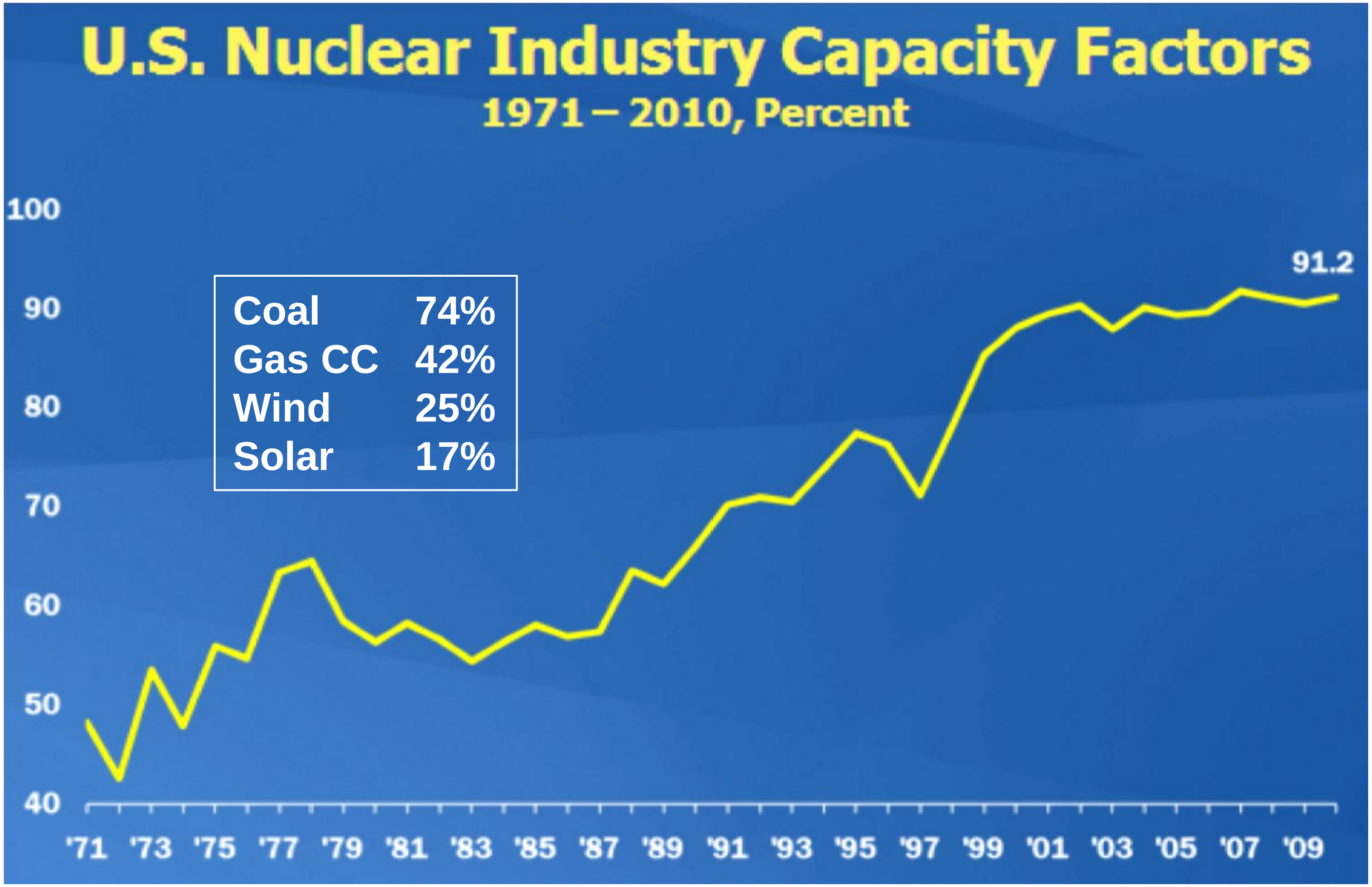
Years of Commercial Operation	Number of Reactors
△ 0-9	0
▲ 10-19	10
▲ 20-29	42
▲ 30-39	52

New England Daily Variation
(Fuel Source for Electricity Generation in 2008)

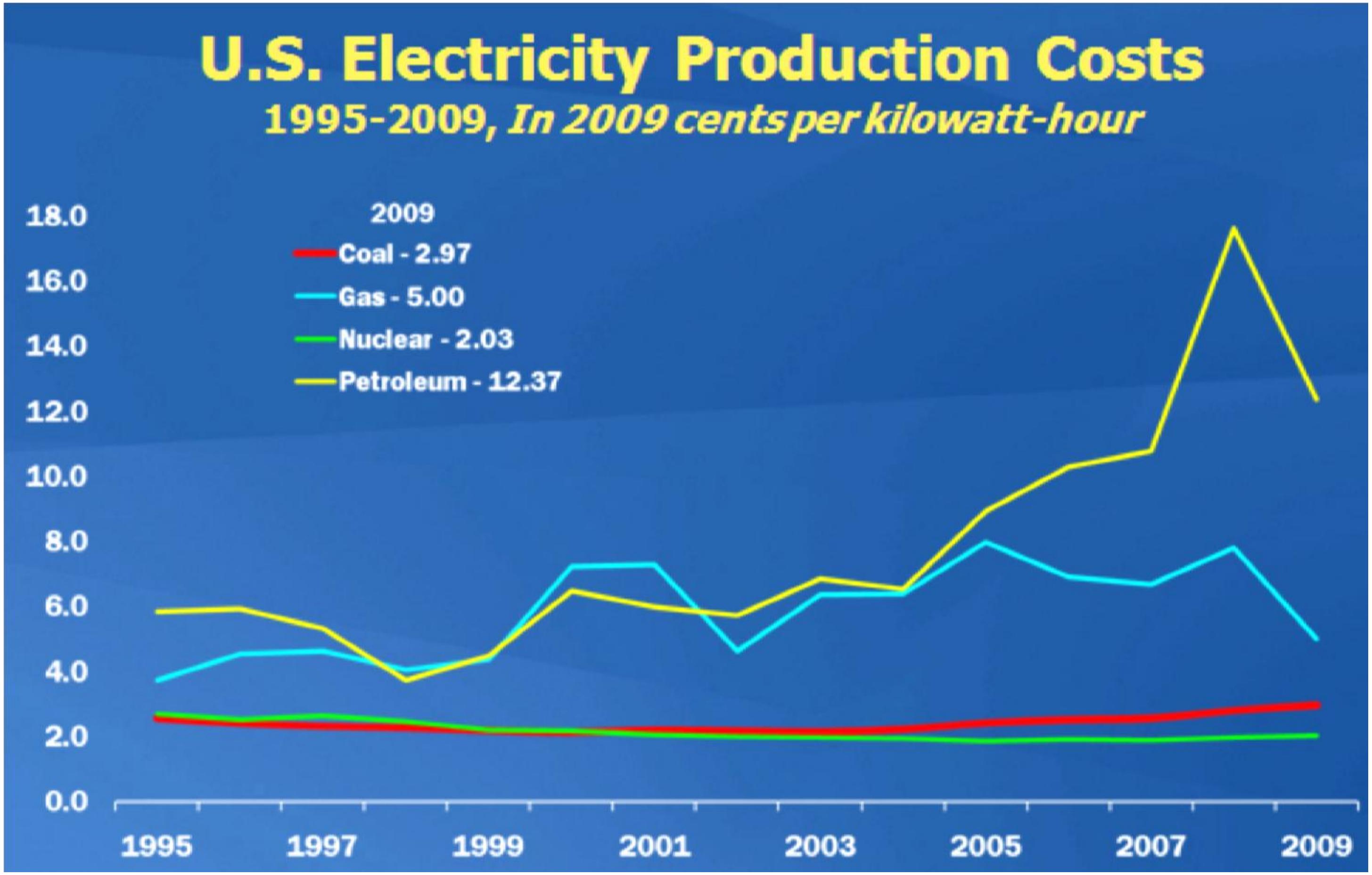


Source: *2008 New England Electric Generator Air Emissions Report*, ISO New England, August 2010.

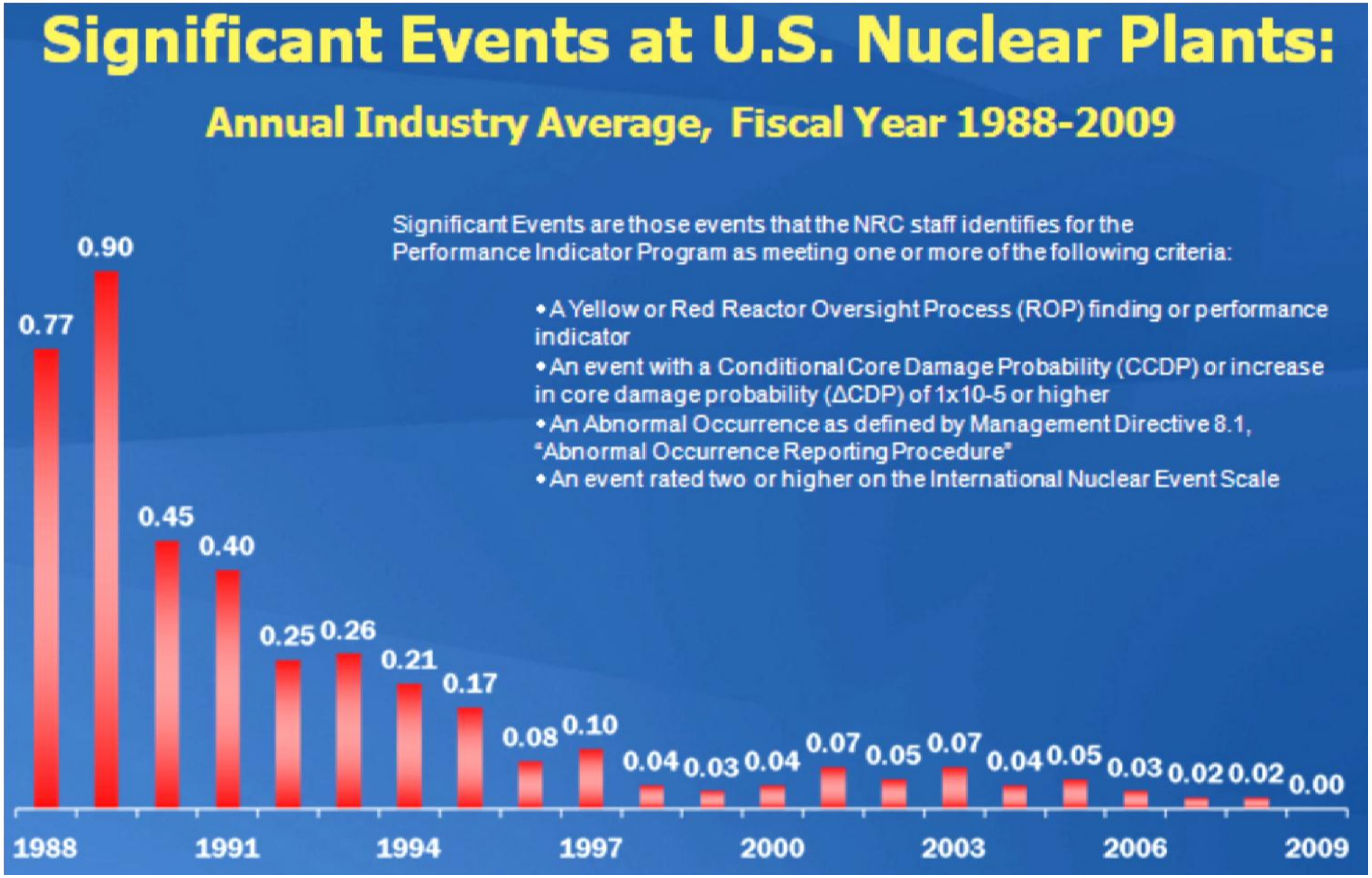
U.S. Nuclear Industry Performance Improvement (Capacity Factors)



Comparison of Production Costs in U.S. by Fuel Type



Significant Safety Events at U.S. Nuclear Plants

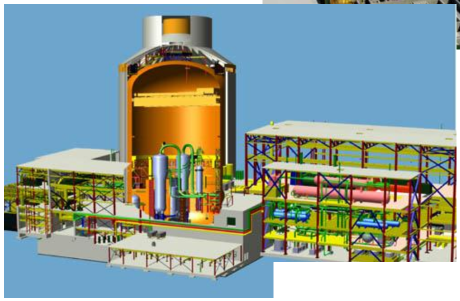


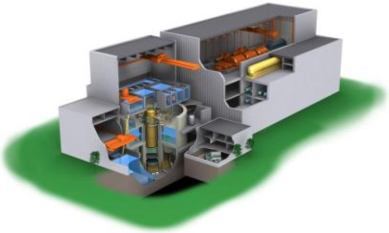
Current Commercial Designs
What Are Their Attributes!

- **Generation III Reactor Designs**
  - Rely on AC electrical power for safety functions – utilize active pumps, valves, and support systems (mostly outside containment)
- **Generation III+ Reactor Designs**
  - No AC electrical power used for safety functions - use natural forces of heat transfer, gravity, evaporation
- **Both Generation III and III+**
  - Have enhanced safety (>10 times better than operating plants)
  - Explicitly address severe accident phenomena to mitigate their consequences
  - Use modular construction and advanced construction techniques


APWR

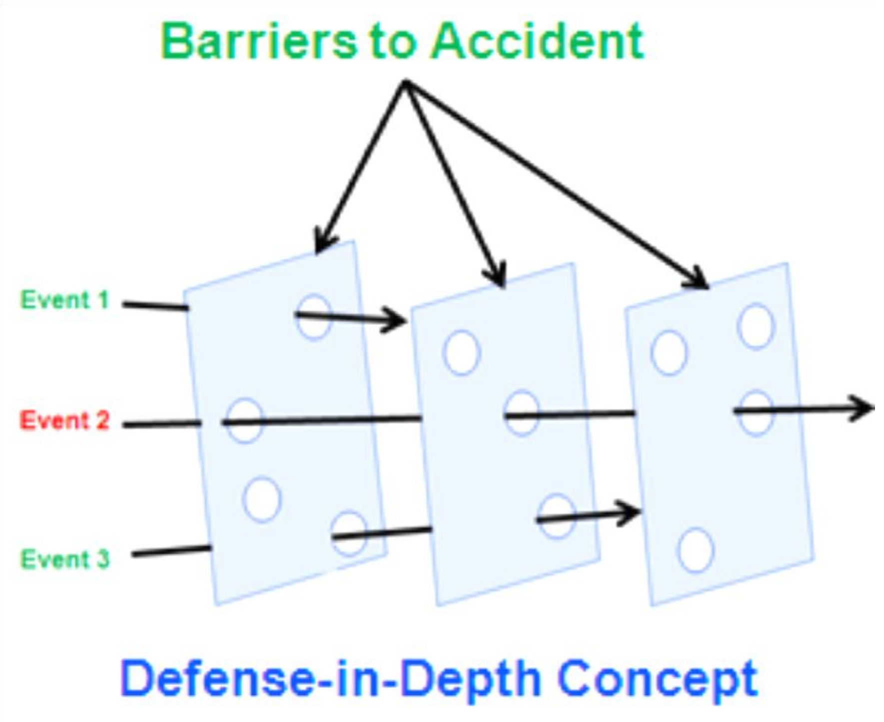

EPR


AP1000


ESBWR

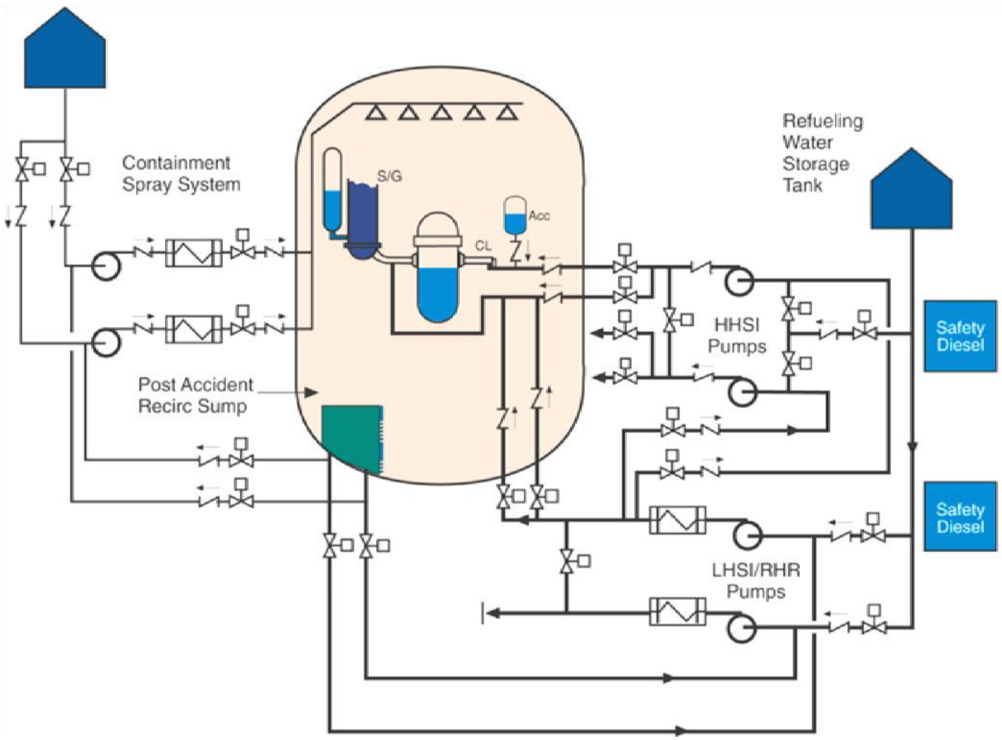
Nuclear Reactor Safety Functions

- Shutdown the Reactor (stop nuclear fission)
- Cool the Fuel (decay heat removal after fission stops)
- Maintain reactor system Integrity (retain water inventory at acceptable temperatures and pressures)
- Maintain containment Integrity (prevent radioactivity release to the environment)

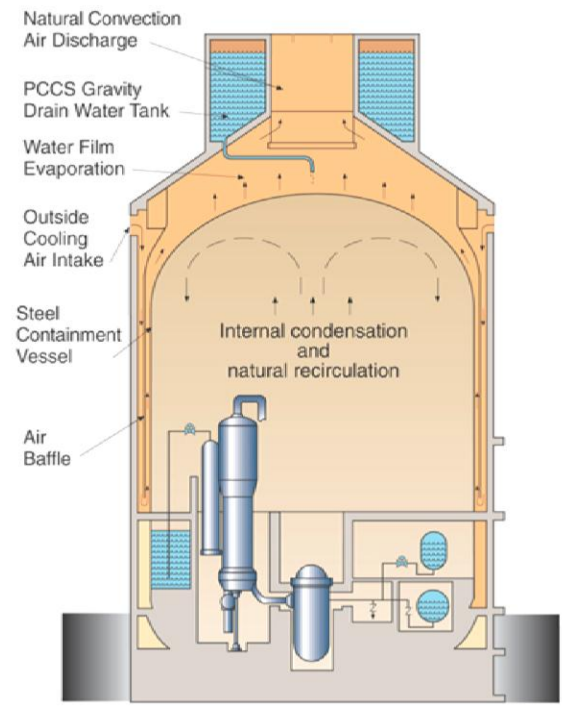


What we strive to do to protect the plant and the safety of the public

Comparison of Active and Passive PWR Safety Systems



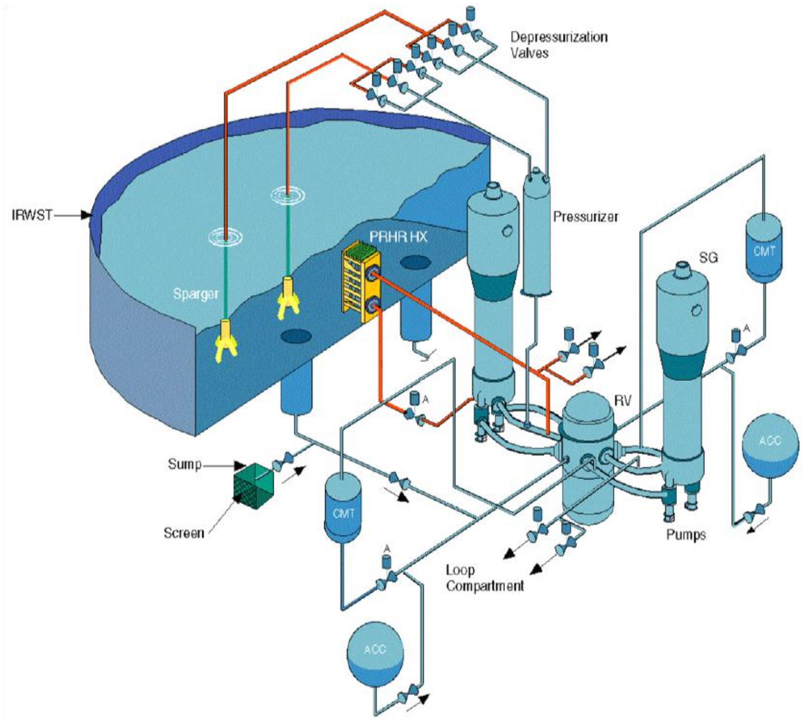
Standard Gen II PWR
(only 2 safety trains)



AP1000
Passive PWR

Passive Core Cooling and Inventory Makeup

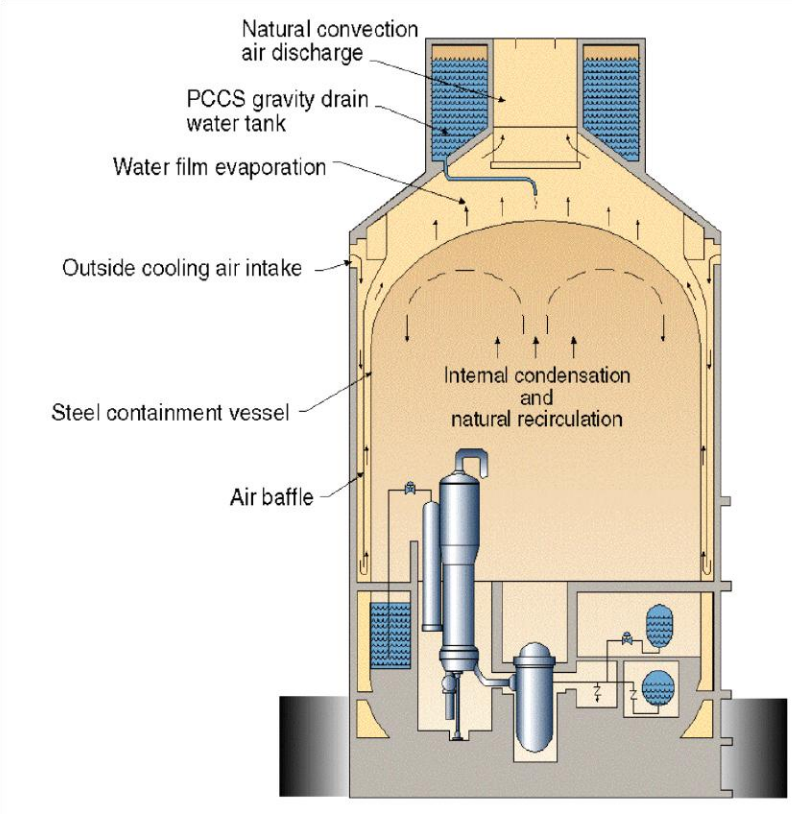
- **All water is already inside containment**
  - **Actuated by levels in tanks, pressure in system, and elevation head**
- **Motive forces are gravity, compressed air, DC batteries, and convective heat transfer**
- **Automatically actuates without the need of operator action**
- **Simple alignment of a few valves which fail in a safe position**



AP1000 Passive Safety Systems

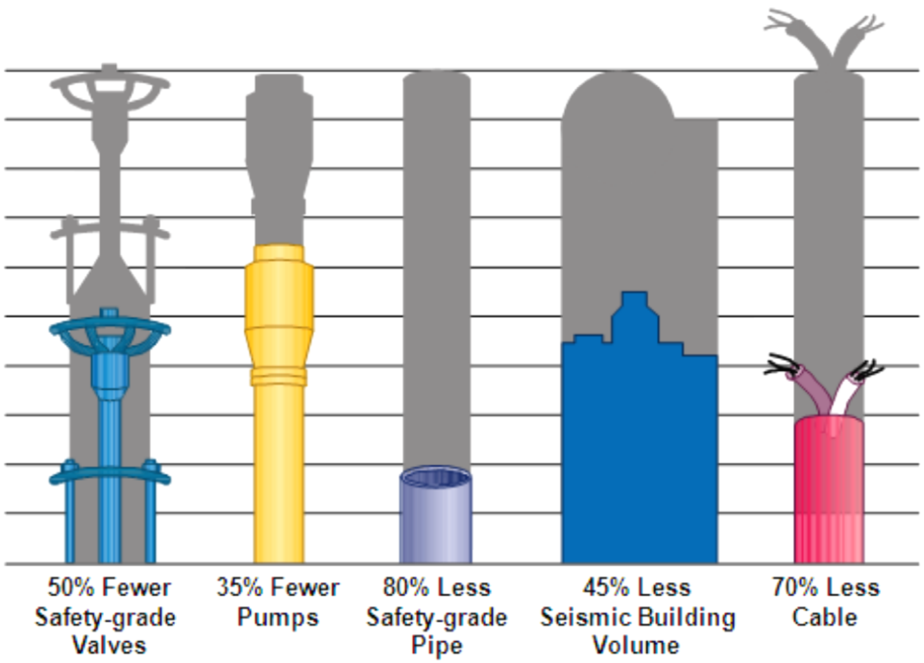
Passive Containment Cooling

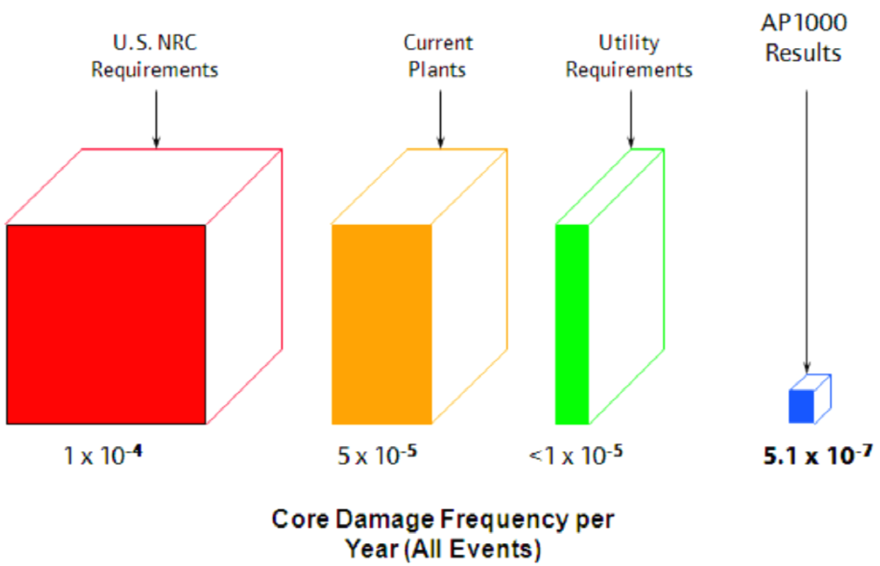
- **Air cooling on outside supplemented by 72 hours of water evaporation**
- **Condensation of steam inside; collecting in large water tank**
- **On/Off-site water available as backup**
- **Proven by extensive testing, analysis, and NRC review**



AP1000 Containment

New Passive Plants Can Achieve Both – Reduction of Cost and Increase in Safety

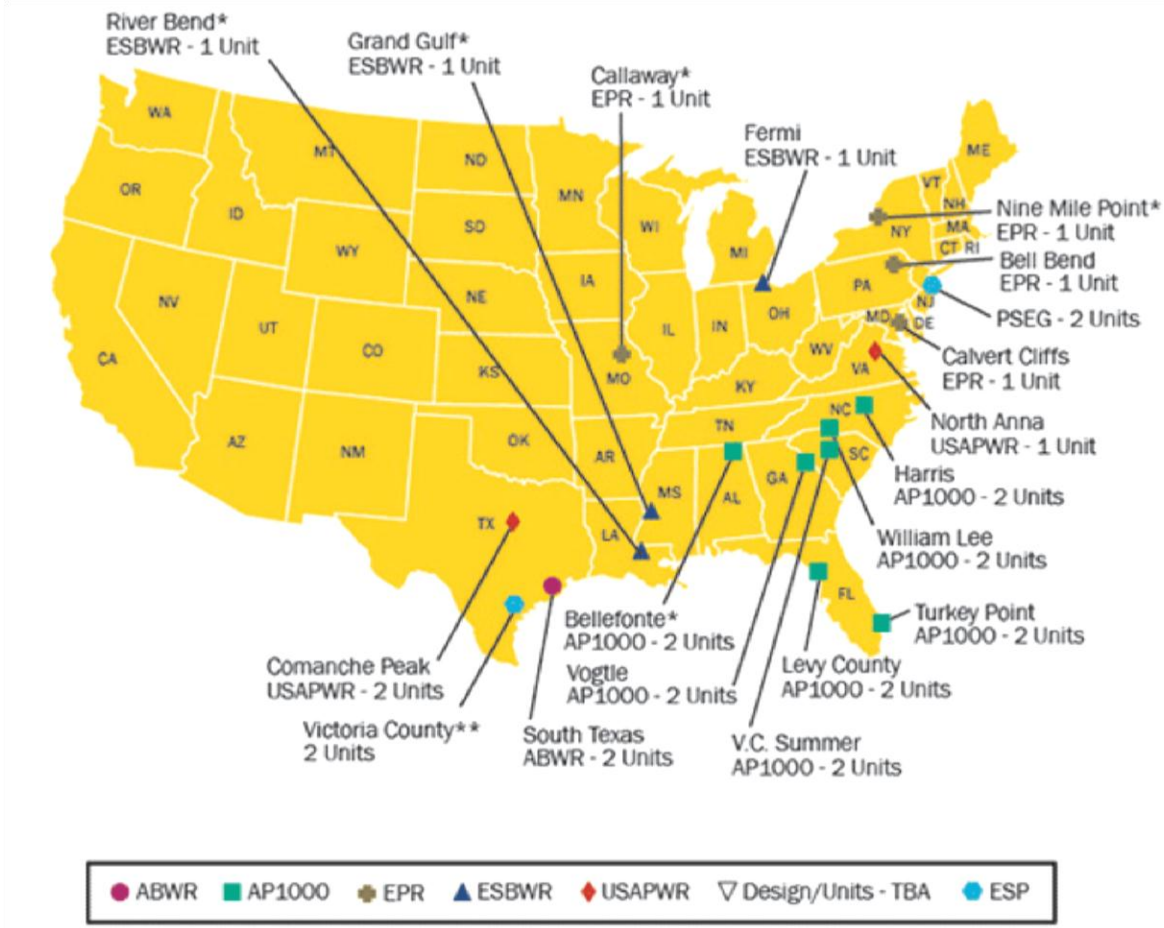




Simplification Reduces Plant Commodities

Passive Systems Enhance Safety

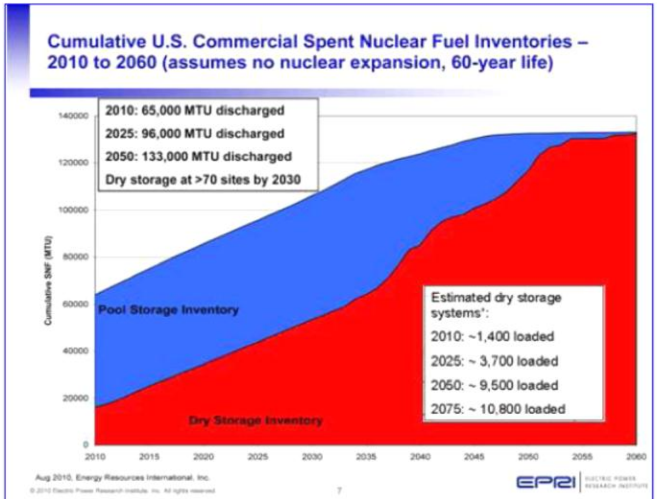
Locations of Proposed New Reactors in U.S.



Key Issues for Expansion of Nuclear Power*

- Continued good performance of existing fleet of operating reactors
- Public confidence, particularly after the Fukushima accident
- Cost of new plant construction
- Cost of domestic natural gas (sets the price of incremental power generation)
- Nuclear waste disposal (storage or geological repository)
- Importance of energy security and greenhouse gas emissions

*How resolved determines pace

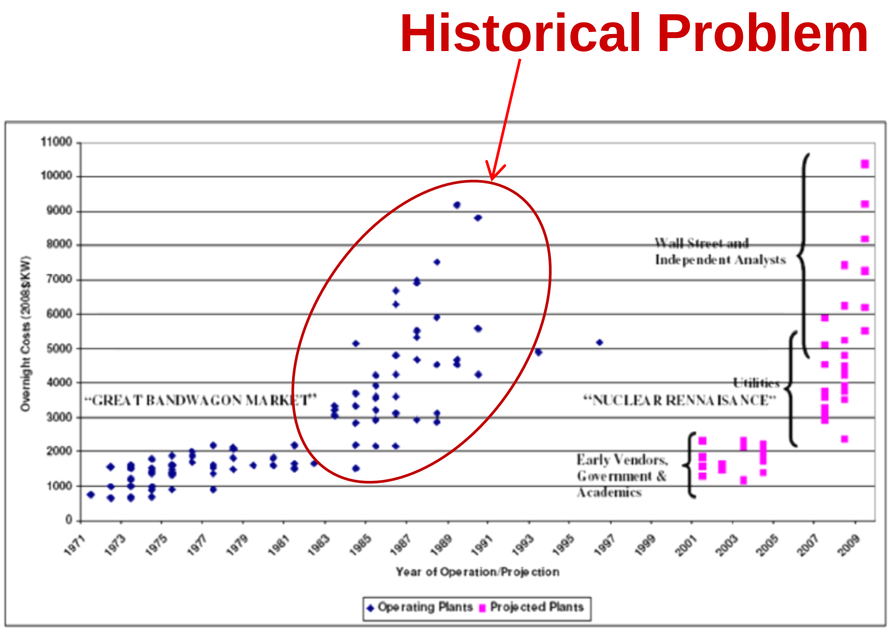


Cumulative U.S. SNF in Storage

25 years of Nuclear Waste
Maine Yankee Reactor

Construction Cost is the Key Issue for New Nuclear Plant Deployment

- New plant construction costs escalated dramatically after the Three Mile Island accident in 1979
  - New regulatory requirements
  - Lack of design completion
  - Ineffective contracting approach
- New regulatory process requires essentially complete design, promotes standardization, and should provide more schedule certainty
- New approach to project implementation has total single entity responsibility to manage schedule and cost risks
- Modern construction techniques can reduce cost and schedule
- Recent construction experience in Asia is good



Construction Cost of New Plants

Comparative Cost of Electricity*
(Levelized Cost, ¢/kWh)

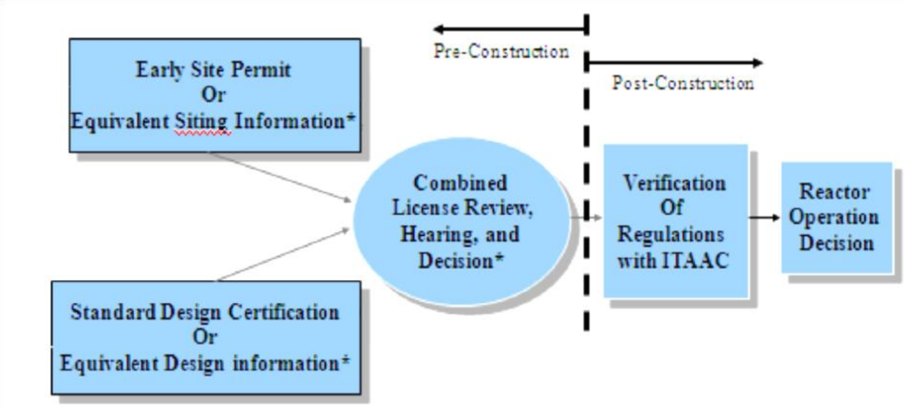
Costs	New Nuclear (w/premium)	New Nuclear (w/o premium)	Coal	CCGT (@$7/$10^6$ BTU)
Capital	6.6	4.9	2.8	1.0
O&M	0.9	0.9	0.8	0.2
Fuel	0.8	0.8	2.6	5.3
Total	8.4	6.6	6.2	6.5

(1) Premium is financial risk premium on capital now placed on nuclear ~3%
(2) At $10/$10^6$ BTU for natural gas, LCOE for CCGT is 8.7 ¢/kWh

*The Future of the Nuclear Fuel Cycle
MIT, 2011

Nuclear Power Policy Issues

- Regulatory Process for Future Reactors
  - Promote Standardization
  - More predictable yet more thorough review
  - Greater public participation
- Waste Disposal Approach
  - Geological repository
  - Dry storage
  - Reprocessing
- National Energy Strategy
  - Security/diversity of supply
  - Greenhouse gas emissions
  - Government support/incentives



NRC Part 52 Licensing Process for New Plants

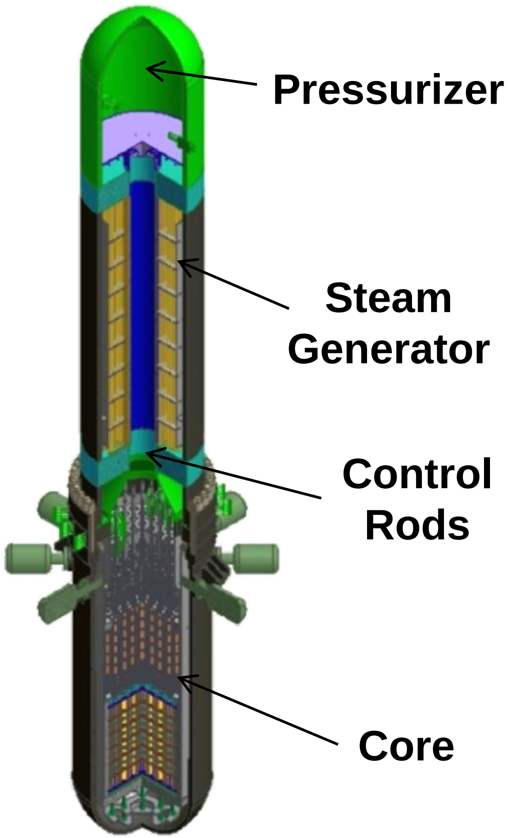
Green = progressing
Red = stalled

Future Innovation is Possible in Three Major Areas

- **Further improvement to large ALWR designs**
  - Further advancements in construction techniques resulting in lower capital costs
  - Design changes to plants like AP1000 to implement improvements and lessons learned, e.g., from Fukushima accident and new construction projects
- **Small Modular Reactors (SMRs)**
  - Simplified passive safety
  - Enables different business models for finance/project deployment
  - Federal cost share support will be important to address First-of-Kind licensing and implementation risks
- **Generation IV Reactors**
  - Must demonstrate potential for economic competitiveness with ALWRs (will likely involve alternative products/fuel cycles)
  - Large hurdles associated with using new fuels/materials
  - Substantial federal contribution required to advance technology

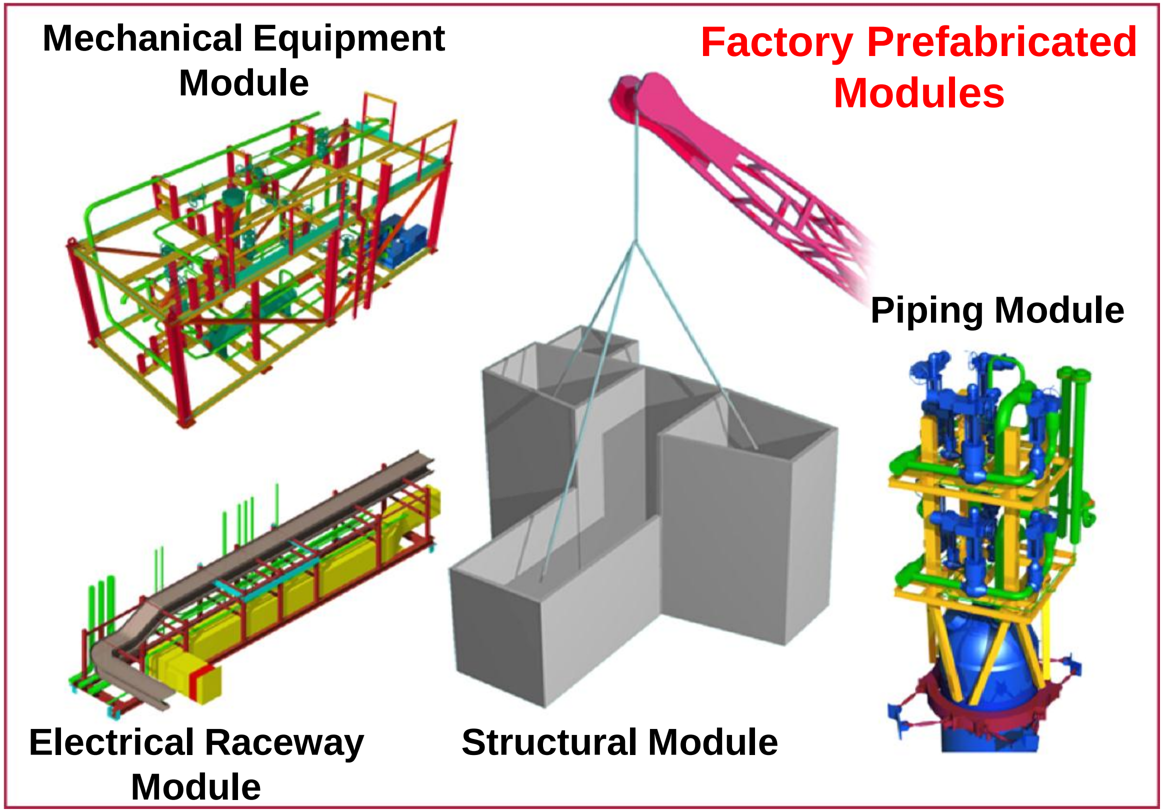
Small Modular Reactors
Starting the Development Cycle

- **Must overcome the economies of scale**
- **Must be water cooled and moderated for mid-term deployment**
- **Must be highly standardized and factory built to control cost and achieve quality**
- **Must have short construction schedule**
- **Must be rail shippable to be broadly accessible**
- **Must use passive safety systems**
- **Must have certain prescriptive regulations revised**
- **Must have smaller Emergency Planning Zone to site near load centers**



Westinghouse SMR

Modular Construction
Major Benefits for New Plants

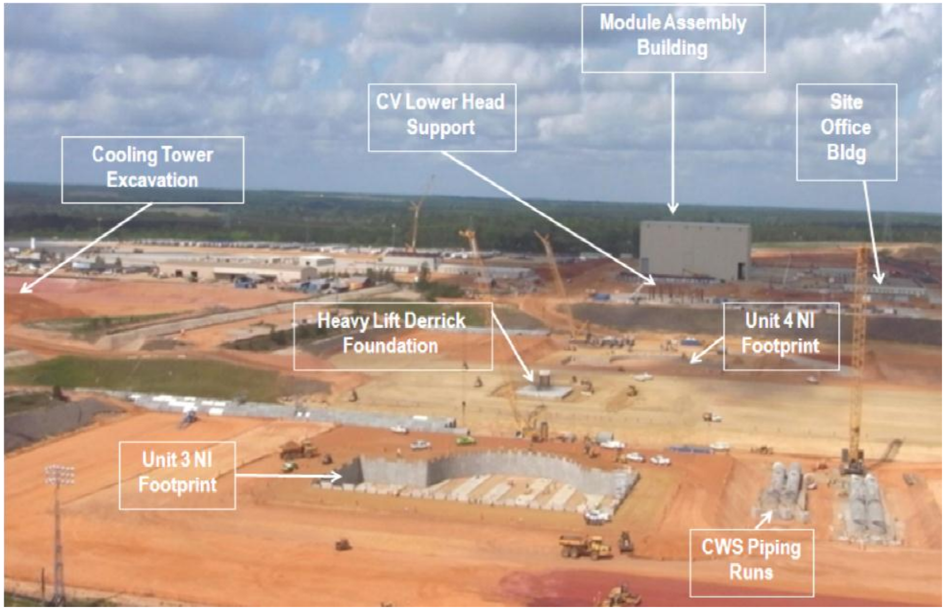


Module Type	Number
Structural	122
Piping	154
Mechanical Equipment	55
Electrical Equipment	11
TOTAL	342

Modules Designed Into AP1000

- Modular design makes site more of an assembly operation
- Allows parallel construction with reduced site craft labor
- Achieve greater schedule certainty and quality control

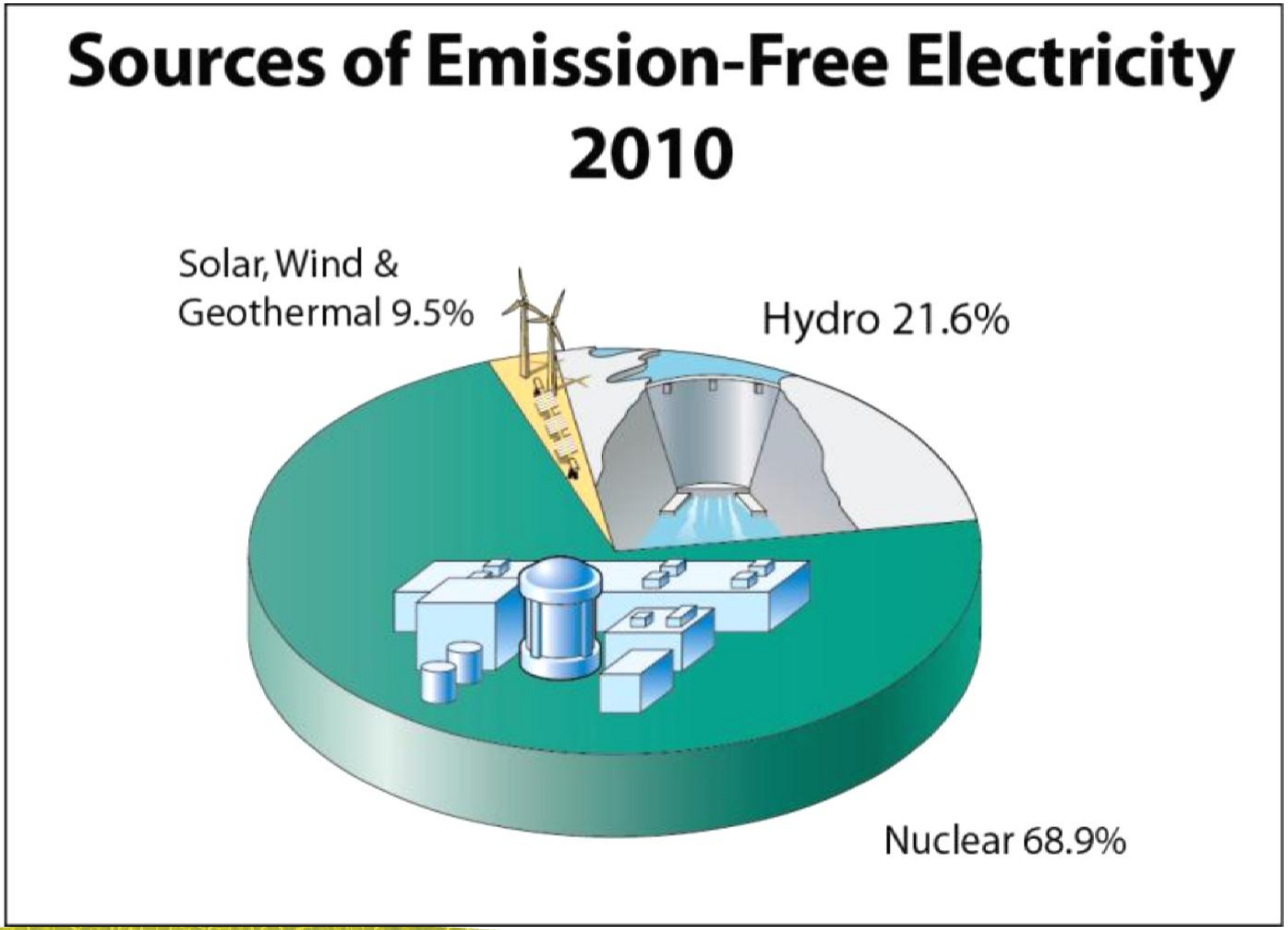
Construction Projects Today
Westinghouse AP1000



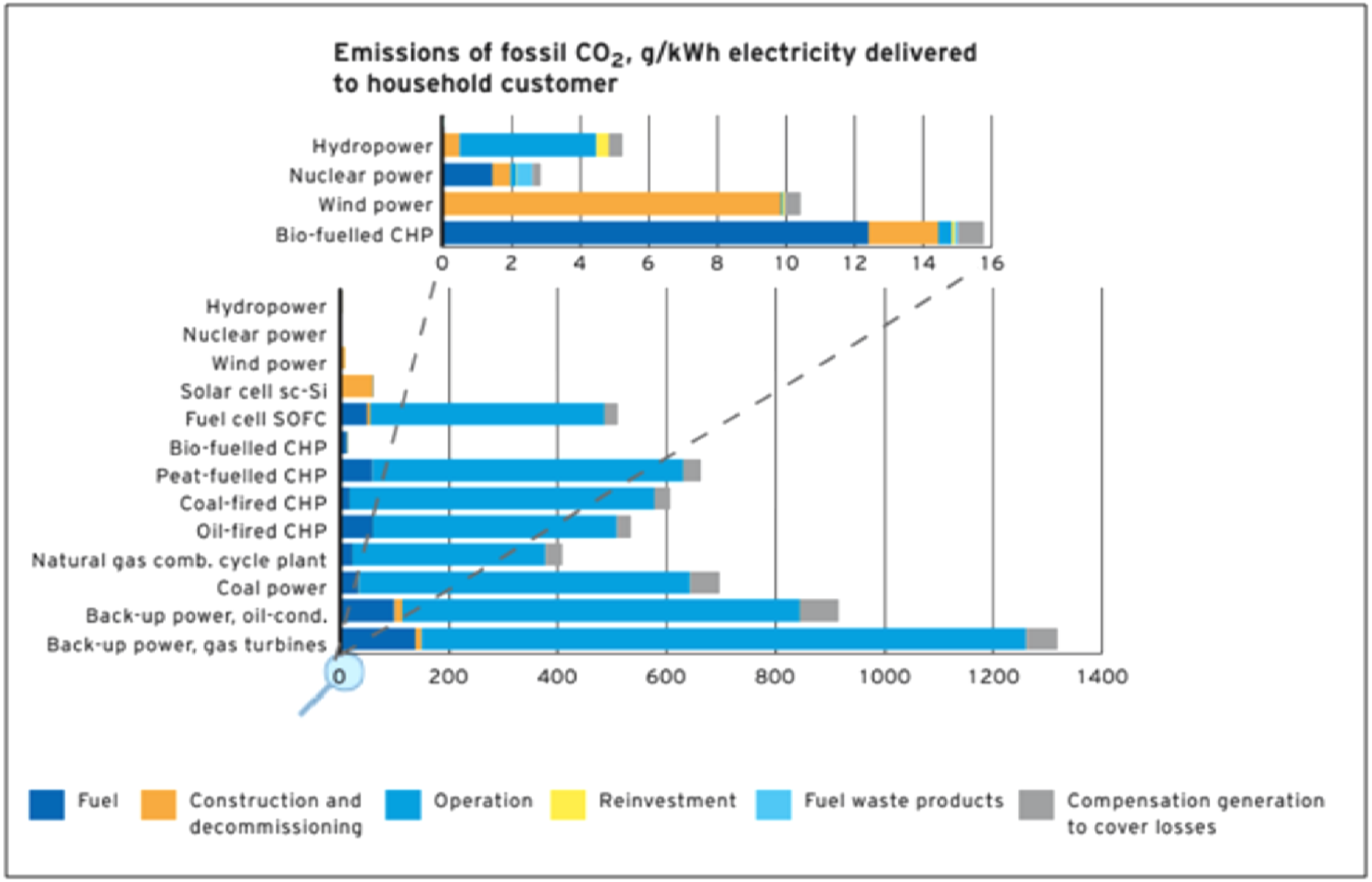
Vogtle Units 3 & 4 now in early stage of construction in U.S. with LWA

Four units now well into construction in China

Where U.S. Gets Its Emission Free Electricity Today

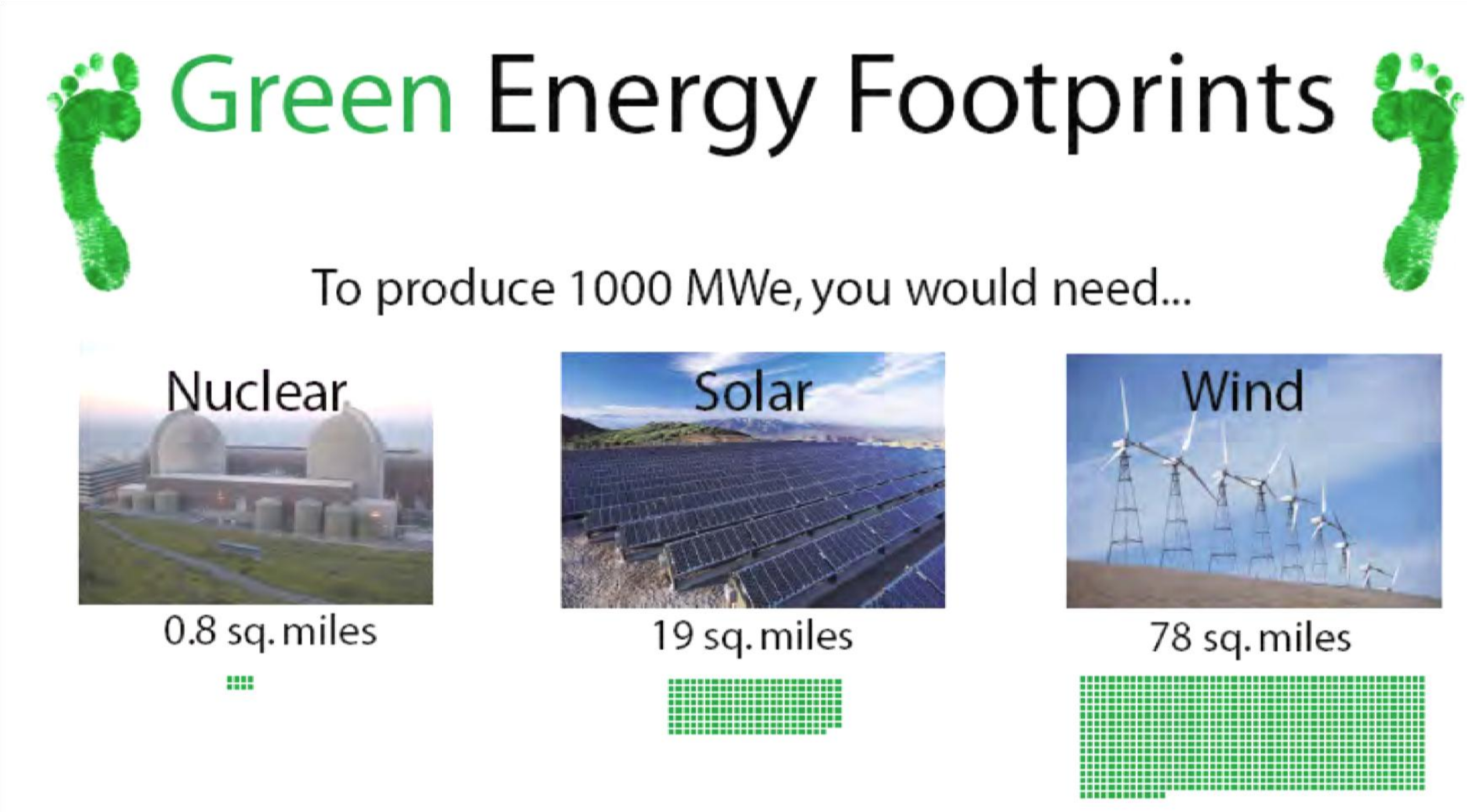


Lifecycle Emissions of CO_2
(per kWh electricity delivered)*



*Vattenfall (2005)

Equivalent Land Area to Produce Same Power



What Remains to Be Done?

- Maintain safe and reliable operation of existing reactor fleet – an absolute necessity
- Successfully deliver the first new reactor projects on schedule and within budget to establish financial market confidence for follow-on projects
- Revise regulatory framework to be risk informed (need a way to credit higher levels of safety) while increasing defense-in-depth against low probability-high consequence events such as Fukushima
- Implement Energy Policy Act 2005 incentives more appropriately to help drive the U.S. nuclear renaissance
- Utilize the lessons learned from the early new plant projects to help ensure the success of follow-on technologies and projects
- Address spent fuel disposition to the satisfaction of the public for both the near term and the long term

Questions?